Supercontinent and Superplate? A short-lived Pangean plate and its role in the supercontinent cycle

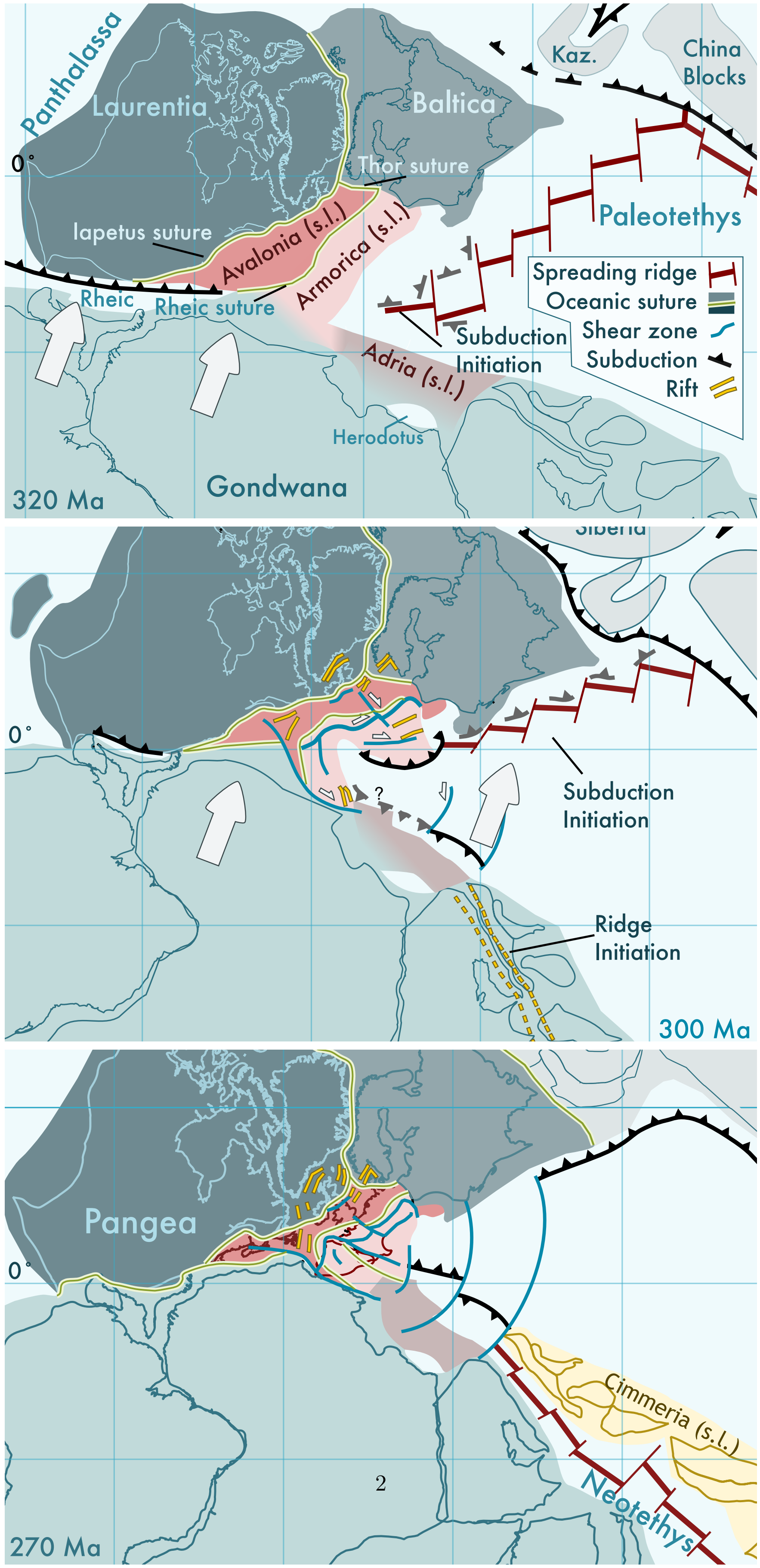
Daniel Pastor-Galán[1,1]

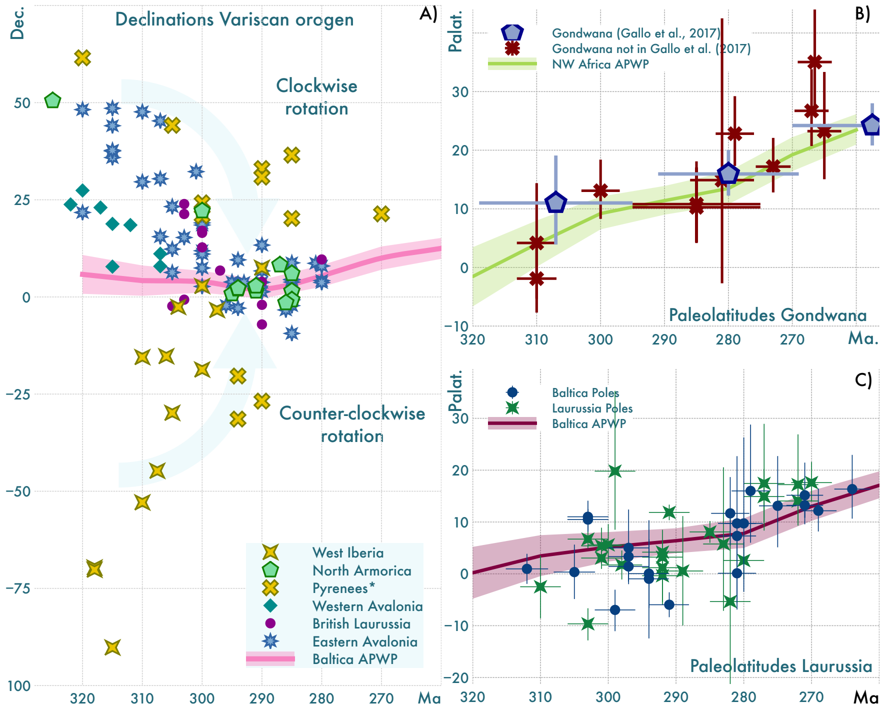
[1]Center for Northeast Asian Studies 41 Kawauchi Aoba-ku, Sendai Miyagi, 980-8576, Japan

November 30, 2022

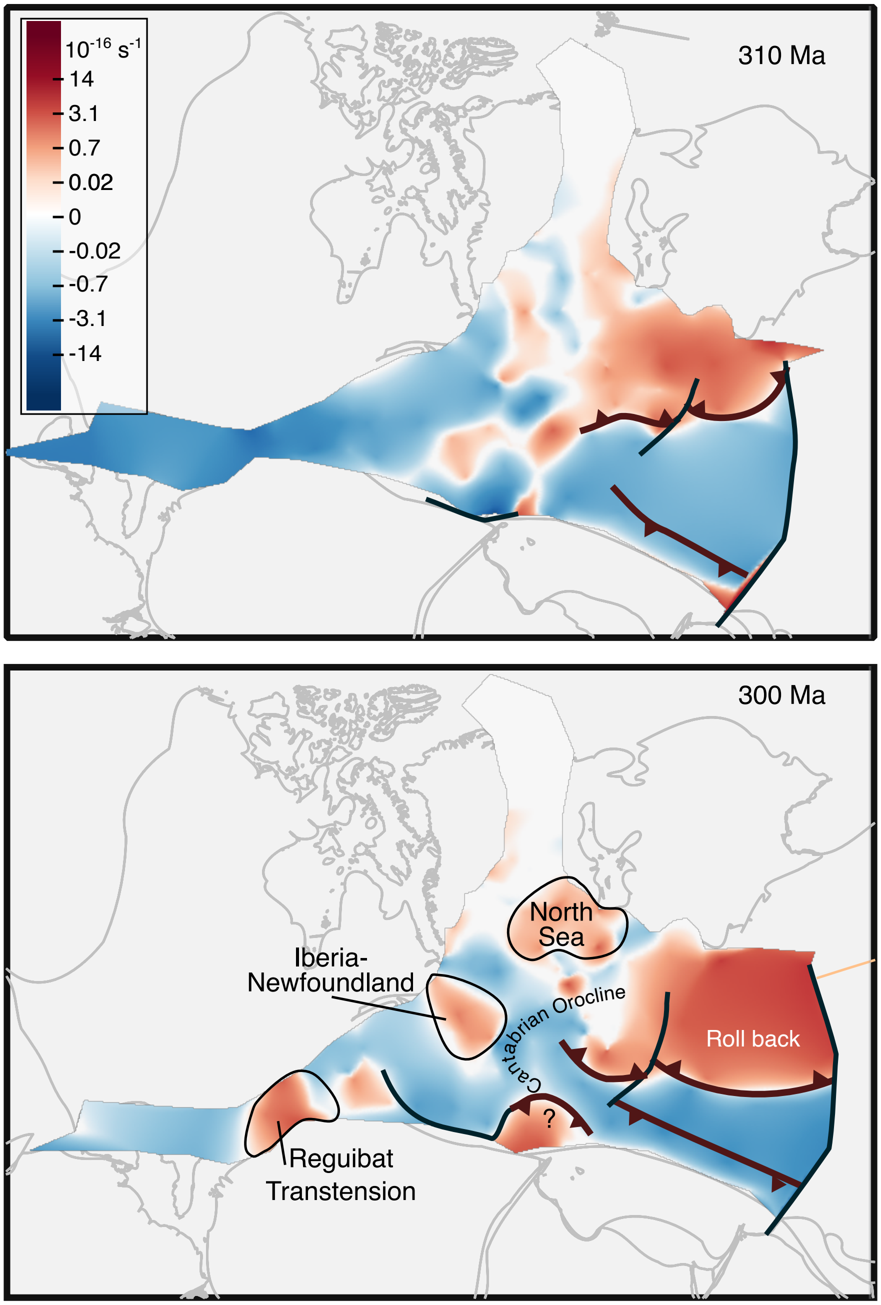
Abstract

The supercontinent cycle explains how landmasses amalgamate into super-plates, which dismember after a ˜100 Myr tenure in a quasi-periodic manner controlling Earth's long-term geodynamics. Pangea, the latest supercontinent, formed ˜330 Ma, began to rift ˜240 Ma finally broke-up ˜200 Ma and it is generally considered the template for all previous supercontinents. The formation of Pangea as a super-plate 330 Ma show a major pitfall: The geologic record between 330-270 Ma predicts >1500km of shortening/extension and shows large volumes of magmatism and metamorphism of unidentified origin. Here I present a tectonic reconstruction that reconciles the inconsistent datasets. In this model, after the initial amalgamation of Pangea the comprising plates kept interacting at least between 320 Ma and 270 Ma, when finally established as a super-plate for a brief period of <70 Myr, which following most recent models would be too short to control the mantle dynamics.

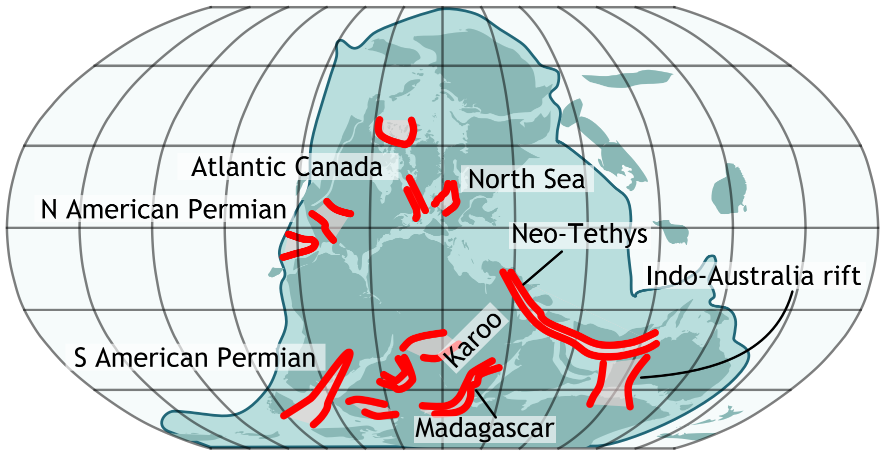

Panthalassa
Laurentia
Baltica
Kaz.
China Blocks
0°
Thor suture
Paleotethys
Iapetus suture
Avalonia (s.l.)
Armorica (s.l.)
Rheic
Rheic suture
Spreading ridge
Oceanic suture
Shear zone
Subduction
Rift
Subduction Initiation
Adria (s.l.)
Herodotus
Gondwana
320 Ma
Siberia
0°
?
Subduction Initiation
Ridge Initiation
300 Ma
Pangea
0°
Cimmeria (s.l.)
Neotethys
270 Ma

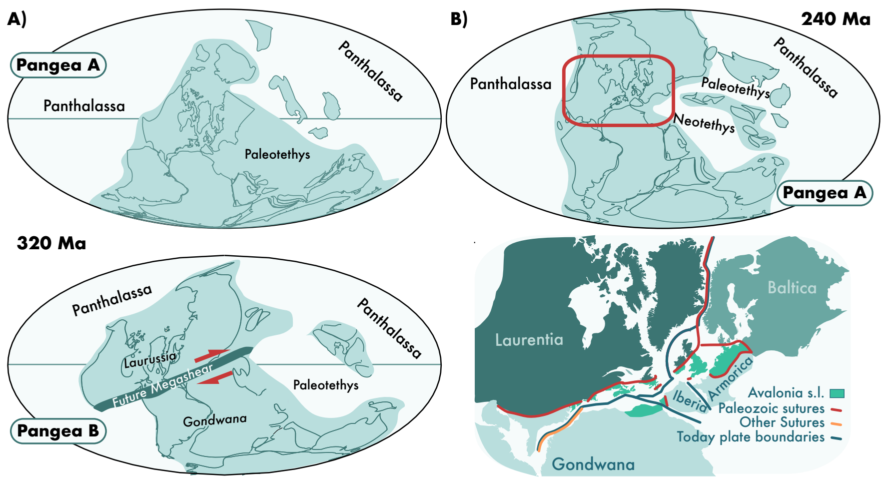


Declinations Variscan orogen
A)
Dec.
Clockwise rotation
Counter-clockwise rotation
West Iberia
North Armorica
Pyrenees*
Western Avalonia
British Laurussia
Eastern Avalonia
Baltica APWP
Ma
B)
Palat.
Gondwana (Gallo et al., 2017)
Gondwana not in Gallo et al. (2017)
NW Africa APWP
Paleolatitudes Gondwana
Ma.
C)
Palat.
Baltica Poles
Laurussia Poles
Baltica APWP
Paleolatitudes Laurussia
Ma



10^{-16} s^{-1}
14
3.1
0.7
0.02
0
-0.02
-0.7
-3.1
-14
310 Ma
300 Ma
North Sea
Iberia-Newfoundland
Cantabrian Orocline
Roll back
?
Reguibat Transtension


Atlantic Canada
North Sea
N American Permian
Neo-Tethys
Indo-Australia rift
Karoo
S American Permian
Madagascar


A)
Pangea A
Panthalassa
Panthalassa
Paleotethys
B)
240 Ma
Panthalassa
Paleotethys
Panthalassa
Neotethys
Pangea A
320 Ma
Panthalassa
Panthalassa
Laurussia
Future Megashear
Paleotethys
Gondwana
Pangea B
Laurentia
Baltica
Armorica
Iberia
Avalonia s.l.
Paleozoic sutures
Other Sutures
Today plate boundaries
Gondwana

Supercontinent and Superplate? A short-lived Pangean plate and its role in the supercontinent cycle

Daniel Pastor-Galán[1, 2, 3]

[1]Frontier Research Institute for Interdisciplinary Science, Tohoku University

[2]Center for North East Asia Studies, Tohoku University, 41 Kawauchi, Aoba-ku, Sendai, Miyagi, 980-8576, Japan

[3]Department of Earth Science, Graduate School of Science, Tohoku University

Corresponding author: Daniel Pastor-Galán (dpastorgalan@gmail.com)

Key Points:

- Pangea was a mobile continent until it became a superplate as late as 270 Ma
- Pangea acted as a single plate for a brief period of time <70 Ma, and likely <50
- The tenure of Pangea's superplate was likely too short to affect the mantle circulation

Abstract

The supercontinent cycle explains how landmasses amalgamate into super-plates, which dismember after a ~100 Myr tenure in a quasi-periodic manner controlling Earth's long-term geodynamics. Pangea, the latest supercontinent, formed ~330 Ma, began to rift ~240 Ma finally broke-up ~200 Ma and it is generally considered the template for all previous supercontinents. The formation of Pangea as a super-plate 330 Ma show a major pitfall: The geologic record between 330-270 Ma predicts >1500km of shortening/extension and shows large volumes of magmatism and metamorphism of unidentified origin. Here I present a tectonic reconstruction that reconciles the inconsistent datasets. In this model, after the initial amalgamation of Pangea the comprising plates kept interacting at least between 320 Ma and 270 Ma, when finally established as a super-plate for a brief period of <70 Myr, which following most recent models would be too short to control the mantle dynamics.

1 Introduction

In the early 20th century, Alfred Wegener presented Pangea ('all lands' in Greek), the "primordial" continent containing all landmasses, whose break-up gave birth to our present-day Earth. Unaccepted for several decades, Pangea became the geologic landmark after the discovery of seafloor spreading and advent of plate tectonics (Pastor-Galán, Nance, et al., 2019). The description of Earth's solid outer shell into rigid plates that move and interact evoking pieces of a spherical jig-saw puzzle (Torsvik et al., 2012; Torsvik & Cocks, 2017) revolutionized Earth sciences and made possible understanding pre-Pangean geology under a unifying paradigm (Evans, 2013). The proposition that other supercontinents might have existed before Pangea, later known as the supercontinent cycle, quickly followed plate tectonics theory. The supercontinent cycle hypothesis proposes that Earth's continental plates amalgamate into single plates with a duration of ca. 100 Myr, which inexorably met their demise when they break apart, in a quasi-periodic cycle that lasts approximately 600 million years (Myr) (Nance et al., 2014). The supercontinent cycle is mostly grounded on indirect geochemical and geochronological proxies whose signatures are not always equivalent (Spencer et al., 2013), mostly because of the limitations of plate reconstructions in pre-Jurassic times (Domeier & Torsvik, 2019). The amalgamation and disruption of supercontinents have been linked to paleogeographical changes in sea-level, biogeochemistry and global climate change (Campbell & Allen, 2008). These external changes do not require any particular geodynamic setting, the mere existence of one super-landmass and its counter super-ocean would trigger most of them. In contrast, geochemical proxies (Gardiner et al., 2016; Spencer et al., 2013) and numerical models (Heron & Lowman, 2010; Heron, 2019; Yoshida & Santosh, 2011) suggest that the formation of super-plates may control the mantle geodynamics and the global plate tectonic circuits. To achieve such an influence on the mantle circulations super-plates need to have no internal lithosphere-mantle interactions during long periods of time (usually >75 Myr) (Coltice et al., 2007; Heron, 2019) and surpass certain size (ranging between 15 and 20% of Earth's surface)(Coltice et al., 2009; Pastor-Galán et al., 2019). This potential links led to develop a supercontinent cycle hypothesis that would drive the long term solid Earth's geodynamics tied to large igneous provinces (LIPs), plume volcanism, deep mantle circulation, outer core dynamics and the evolution of Earth's magnetic field(Philip J. Heron, 2019; Pastor-Galán, Nance, et al., 2019). However, and despite their potential importance, all these links are permissive rather than proven.

Pangea, the most recent continental super-plate, has logically played a crucial role in the development of the supercontinent cycle hypothesis. It remains the best constrained supercontinent, whereas other pre-Pangean supercontinents are kinematically less known(Evans, 2013). Pangea's disassembly is well understood owing to the preservation of the ocean floor that grew between its components (Müller et al., 2019). In contrast, the amalgamation and tenure of

Pangea remains puzzling, the plate kinematics and mechanisms responsible for its formation are contradictory resulting in a long term debate on how the Pangean super-plate formed and its geodynamic consequences (Domeier et al., 2012; Yoshida & Hamano, 2015). In this paper, I present a plate reconstruction that reconciles paleomagnetic and geological data and shows that Pangea was likely a short lived super-plate, in spite of being a long-lived, but tectonically active, large landmass.

2 The Two faces of Pangea

The geometry and kinematics of Pangea previous to its break-up are reasonably constrained. In the early Mesozoic era (ca. 240 Ma) extension commenced in Pangea's between present-day NW Africa and North America (Kneller et al., 2012; Müller et al., 2019). After a protracted period of extension of about 40 Myr, oceans arose in the Early Jurassic (Müller et al., 2019) assisted by plume magmatism originated above the Large Low Shear Velocity Province (LLSVP) known as TUZO (Burke, 2011; Burke et al., 2008), to end now, with its former constituents dispersed and globally distributed (Torsvik et al., 2012).

Pangea's amalgamation occurred during most of the Paleozoic era with a series collisions between the existing continents (Gondwana, Siberia, Laurentia, Baltica, Avalonia (s.l.), and other minor plates). The Devonian-Carboniferous collision of Gondwana and the previously amalgamated Laurussia (Laurentia, Baltica and Avalonia), the two largest continents at the time, formed a large orogeny in the core of Pangea (Fig. 1). The collision zone became a 1000 km wide and 8000 km long global-scale orogenic system (Variscan, hereafter) whose fragments are now dispersed over Europe, Africa and North America due to the Mesozoic break-up of Pangea (Fig. 1) (Domeier & Torsvik, 2014; Weil et al., 2013). The Variscan formed as a consequence of a continued tectonic history that involved the consumption of at least one major ocean, the Rheic, commencing at 420 Ma and whose mid-oceanic ridge subducted at ca. 395 Ma along its paleo-northern margin(Nance et al., 2010). Most tectonic reconstructions assume Pangea being a single and stable super-plate from ca. 330 Ma(Domeier et al., 2012; Stampfli et al., 2013; Wu et al., 2020). However, this hypothesis of a Pangean super-plate from ca. 330 Ma is not consistent with many observations:

1) The continent-continent collision after closure of all intervening oceans was diachronistic and became progressively younger westwards (in present-day coordinates): from Devonian along the eastern boundary, progressing to Early Permian ages in the westernmost sector (Pastor-Galan et al., 2015).

2) An enhanced thermal regime with widespread post orogenic (between 310 to 270 Ma) but not plume related magmatism in the core of Pangea (Weil et al., 2013) was accomapanied by particularly hot high pressure metamorphism (Tsujimori & Ernst, 2014).

3) Paleomagnetism, which informs about paleolatitudes and vertical axis rotations of continents, can quantify past motions between continental blocks if they are not connected to oceanic crust through a passive margin. Paleomagnetic data show significant vertical axis rotations that imply thousands of kilometers of shortening and /or extension (depending on the location of the Euler poles)(Pastor-Galán et al., 2018) within the super-plate (Fig. 2). Coevally globally distributed Late Carboniferous and Permian basins developed. In addition global Paleozoic paleomagnetic data from stable continents have consistently shown >1000 km

latitudinal overlaps between Gondwana and Laurussia in conventional Pangea reconstructions (known as Pangea A models) (Domeier et al., 2012; Gallo et al., 2017; Kent & Muttoni, 2020).

To accommodate the paleolatitudes imposed by the paleomagnetic data, some authors suggest a different framework, the Pangea B model, in which Laurussia would locate to Gondwana's far-west (Fig. 1) (Gallo et al., 2017; Kent & Muttoni, 2020). The transition from a Late Carboniferous Pangea B to the unanimously agreed Pangea A configuration at the Permo-Triassic boundary(Kent & Muttoni, 2020; Müller et al., 2019) requires >3500 km of right-lateral displacement between Laurussia and Gondwana through one (or a series of) megashear zone(s) (Fig. 1). Pangea B reconstructions acknowledge the internal mobility of Pangea during the Permian but they are incompatible with the observed vertical axis rotations and associated shortening and extension in the interior of Pangea(Domeier et al., 2012). In addition, geologic evidence allowing Pangea B, so-designed to fulfill paleomagnetic criteria, is critically lacking: Paleobiology evinces strong affinities between late Paleozoic flora of north-west Africa and western Europe–eastern North America (Correia & Murphy, 2020), and similarities in Permian fauna in southern North America and northwestern South America. Whereas the European Tethyan realm (Greater Adria) shows affinities with central Asia(Angiolini et al., 2007). Stratigraphic and provenance analyses also link late Paleozoic sedimentary styles and facies between southern North America and northwestern South America, and between northern Africa and western Europe–eastern North America (Correia & Murphy, 2020; Domeier et al., 2012). Pangea B faces its most serious challenge in the absence of structural evidence for a ~3500 km dextral megashear zone between Gondwana and Laurussia. Despite the good exposure of the collision zone between Gondwana and Laurussia, the only right lateral motion and shear zones are Late Carboniferous to Early Permian, rather than the necessary middle to late Permian age to justify the movement (Kent & Muttoni, 2020). In addition, such right lateral motion estimated in <700 km (Matte, 2001) is far below the necessary >3500km. Pangea B model also requires the previous southeast North America (Ouachita–Marathon) facing the Panthalassa Ocean (Fig. 1), the Appalachians juxtaposed with the northern Andes, and the European Variscan opposed western Africa (Fig. 1). Finally, most data support a tectonically stable Pangea interiour from the Middle Permian (~270 Ma) to the Middle Triassic (~240 Ma) (Ziegler, 1990).

3 Plate kinematic constraints

This paper reconstructs plate configurations at Pangea's interior between 320 and 270 Ma with a paleomagnetic reference frame supported by multiple geologic observations and semiquantitative data. The plate circuit of this paper's model ends in South Africa, . In the paper we provide two options for the movement of South Africa (see Materials and methods).

3.1 Paleomagnetism

For the reconstruction of the inner Pangean kinematics between 320 and 270 Ma, I used the most recent global compilation of paleomagnetic poles for the Phanerozoic (Torsvik et al., 2012) And a compilation of all available paleomagnetic data from the Variscan orogen, from Poland to Iberia and the Atlantic coast of North America, in the time from 330 Ma and 280 that met a minimum of quality pre-requirements (See Materials and Methods). Paleogeographically, the newly compiled data come from both Gondwana and Laurussia margins, most of them from the area putatively deformed by shearing during the Pangea B to Pangea A transition in the middle Permian. The reconstruction fulfills all paleomagnetic constraints, both from the orogenic areas (Fig. 2) and from stable Laurussia and Gondwana, including those suggesting large overlaps in classical Pangea A reconstructions (Fig. 1). Paleomagnetic poles used in the paper and their references are listed in Table S1.

Paleomagnetism supports a general northwards drift of Gondwana during the late Paleozoic. In contrast Laurussia apparently kept its latitude moving roughly E-W, at least until the Early Permian (Torsvik & Cocks, 2017), when it started moving northwards together with Gondwana until the break-up of Pangea. The reappraisal of the paleomagnetic observations from 330 Ma to 270 Ma in the Variscan orogen shows vertical axis rotations with respect to the magnetic pole of continental blocks that affected the majority of the orogen, a vast area within Pangea (ca. 7.5 x 106 km2; Figs. 1 & 2). This paleomagnetic dataset shows compatible paleolatitudes in the collision zone between Gondwana and Laurussia (Fig. 2; SF1). Data from NW Europe show a consistent ~30° clockwise rotation at 320 Ma. The magnitude of rotation decrease on time until it gets 0 in all magnetizations younger than 270 Ma (Fig. 2) which are considered the upper and lower bounds for it. The rotation affected the majority of Gondwana and Avalonia s.l. (a former 'ribbon continent' that constituted the Laurussian southern realm Fig. 1). Late Carboniferous clockwise rotation also occurred in the original Laurentian margin (present day Scotland, and northern half or Ireland), but only the areas located in the vicinity of major Carboniferous structures seem to be affected (Figs. 2 and 3). Most of the Iberian peninsula, SE France, Corsica and Sardinia show coeval and opposite sense counterclockwise rotations of about 90°. In the NW of the Iberian peninsula, it is possible to observe both in its geometry and through differential vertical axis rotations, the change in trend (Weil et al., 2013). In most of the reassessed cases, paleomagnetic data were disregarded due to their secondary origin (i.e. coming from older rocks that were remagnetized in the Carboniferous). In the other cases, the observed rotations were considered local effects, and therefore of minor significance in global tectonics (Edel et al., 2018) or even supportive of Pangea B, despite showing no paleolatitude incompatibilities (Bachtadse et al., 2018). Satisfying the late Carboniferous-early Permian vertical axis rotations that paleomagnetic data indicate requires large scale movements within Pangea. The motion would involve >2000 km of convergence and >1000 km extension accommodated somewhere at Pangea’s interior after its alleged stability (ca. 330 Ma). however, that deformation is yet to be localized.

3.2 Geology

The subduction of the Rheic ocean relics and development of the Variscan (s.l.) orogen accommodated the oblique convergence between Gondwana and Laurussia during the Late Paleozoic(Nance et al., 2010). At the end of Carboniferous, the convergence imposed by the continuing northwards motion of Gondwana buckled the Variscan orogen affecting both margins and likely accommodated several hundreds of kilometers of shortening at a lithospheric scale (Pastor-Galán et al., 2020; Weil et al., 2013), a structure that is especially visible in the westernmost Europe (Edel et al., 2018). Other consequences of the north-south convergence in the late Carboniferous to early Permian include the closure of the Junggar Ocean (Chen et al., 2014), and the bending/buckling the Kazakhstan arc in the Central Asian Orogenic Belt (Li et al., 2018).

Widespread transpressional and transtensional lithospheric scale structures also formed in the time between 320-270 Ma. The main strike-slip motion within the core of Pangea is right-lateral(Matte, 2001) owing to the E-W convergence imposed by Laurussia. Most of these faults follow the curved trend of the orogen suggesting accommodation of vertical axis rotations (Gutiérrez-Alonso et al., 2008; Turrillot et al., 2011). Restoration of slip displacement along the faults brings the European Variscan belt into continuity with the Moroccan and North American sections of the belt (Gutiérrez-Alonso et al., 2008).

In addition to shortening and wrenching, many areas of inner Pangea underwent extension that led to the formation of over 100 rift basins (Lamotte et al., 2015) (Fig. S2). Major Permian extensional and rift basins include the North Sea and Oslo rift, the Rotliegend areas (from Netherlands to Poland), the conjugate margins between Iberia and Newfoundland, the large Karoo system from Arabia to South Africa, and the Neotethyan basin that opened along the Paleo-Tethys southern margin (from Arabia to Australia) (Lamotte et al., 2015).

In E North America and Europe, the areas most affected by Late Carboniferous-Permian post-Variscan shortening, strike-slip or extensional tectonics a magmatic pulse that peaked at ca. 310–270 Ma has been recognized. Voluminous mafic to granitoid intrusions were emplaced together with their extrusive equivalents both the internal and external zones of the orogen (Boscaini et al., 2020; Gutiérrez-Alonso et al., 2011; Wilson, 2004). Although this tectono-thermal event has been linked with the orogenic collapse of the Alleghenian–Variscan–Ouachita belt or with a plume event, the collapse of the Variscan belt in Europe finished at the earliest Pennsylvanian (Pastor-Galán et al., 2019) and the geochemical data from the magmatic rocks, especially in northern Europe, is not compatible with the involvement of a mantle plume (Gutiérrez-Alonso et al., 2008).

In southern and western Europe the magmatic pulse is compatible with subduction, delamination and/or slab break off (Boscaini et al., 2020; Gaggero et al., 2017; Pereira et al., 2014). Late Pennsylvanian to middle Permian rift basins also show an extensive and significant, but short (305-270 Ma) magmatic pulse accompanying the extensional phase(Zeh et al., 2000) that sometimes trespassed the basins extent like the Permian dyke and sill complexes of Northern England and Scotland (Lamotte et al., 2015). In the particular case of the Neotethys rifting, plume volcanism is indeed involved. The Panjal Traps, present day NW India, occurred at 289 ± 3 Ma in the southern realm of the Paleotethys ocean (Yeh & Shellnutt, 2016), and possibly assisted the lithospheric extension and further opening and development of the Neotethys ocean.

High Pressure (HP) metamorphism, ophiolite obduction and arc inception occurred along the Paleotethys realm within the period 320-270 Ma(Jian et al., 2008; Shafaii Moghadam & Stern, 2014; Zhang et al., 2016). HP rocks are commonly found in Iran and China, coevally the Jinshajian and Xiangtaohu supra-subduction ophiolites obducted (~300-280 Ma). All these processes suggest subduction initiation, ridge failure, and/or ridge subduction events accommodated the northwards movement of Gondwana and the plate reorganization after the formation of the Pangean super-plate. Subduction initiation/ridge subdution of the Paleotethys occurred concomitantly to the rifting of the Neotethys(Gutiérrez-Alonso et al., 2008). The previous subductionand obduction record together with the Late Carboniferous and Permian development of the Meliata Arc, E Europe, suggest a northwards directed subduction initiation and/or ridge subduction. In contrast, recently described arc magmatism in the Pontides (present day Turkey,) proves subduction with south polarity at least in the Paleotethyan southern realm below Greater Adria (van Hinsbergen et al., 2020). Other relics of southwards subduction have not been found yet along the Paleotethyan southern realm.

Other occurrences of HP metamorphism at that time span are preserved in the Central Asian Orogenic Belt (CAOB) and within Panthalassa (Nipponides) (Isozaki et al., 2010; Li et al., 2018). A very particular feature of the late Carboniferous and Permian HP rocks is a global lull of lawsonite blueschists (Tsujimori & Ernst, 2014). The global lawsonite hiatus is a robust indication of relatively warm subduction-zone thermal regimes at this time globally (Tsujimori & Ernst, 2014).

In the model presented in this paper, the Paleotethyan subduction appears segmented with different polarities depending on the realm since it was the simplest kinematic solution. However, it cannot be ruled out subduction towards both north and south along the entire Paleotethys.

4 Discussion and Conclusions

Most geologic disciplines long backed that Pangea amalgamated at ~330 Ma and remained for over 130 Myr as a single plate until its early Jurassic break-up, attributing unknown biases to paleomagnetic data (Domeier et al., 2012) or local scope to structural and/or petrologic data (McCann et al., 2006). Despite the Pangea A agreement among the geologists, the structural, petrologic and geochronologic data provided here, support that substantial areas of Pangea kept intensively deforming during the late Carboniferous and early to middle Permian. to become internally stable at ca. 270 Ma (Gutiérrez-Alonso et al., 2008; van Hinsbergen et al., 2020). During that time interval: (1) large amounts of lithospheric scale shortening formed orogenic transects in western Europe, North Africa and Southeastern North America(Pastor-Galán et al., 2018, 2020); (2) large amounts of post-collision magmatism occurred in the Variscan belt (e.g. Boscaini et al., 2020); (3) Oceanic rocks within the intra-Pangea Paleotethys ocean obducted and exhumed (Zi et al., 2012); (4) extension and rifting occurred in the present day North Sea, Atlantic Canada-Iberia conjugate margins, eastern Africa and west Australia, and the southern realm of the Paleotethys, which after a protracted extension gave rise to the break-apart of a ribbon continent (Cimmeria) and the opening of the Neotethys Ocean (Lamotte et al., 2015).

The plate model of this paper proposes that Gondwana, with a northwards trajectory through the late Paleozoic (~400 to 250Ma)(Torsvik & Cocks, 2017) and Laurussia, roughly E-W during Carboniferous times (~360 to ~300 Ma)(Torsvik et al., 2012), collided and caused a diachronous westward-younging collision (Edel et al., 2018; Wu et al., 2020). leading to orogenesis, from Late Devonian (in eastern Europe) to the early Permian (southeastern North America) (Nance et al., 2010). The obliquity of the collision and the incessant northwards motion of Gondwana, caused a plate tectonic reorganization penecontemporaneous to the Pangea amalgamation. The Rheic Ocean, which separated both Gondwana and Laurussia continents, closed in a 'zipper' style through the late Paleozoic (Domeier & Torsvik, 2014) (Fig. 3 and Supplementary Videos). During the late Carboniferous, the deformation at the increasingly coupled Gondwana and Laurussia boundary could no longer accommodate the quick northwards motion of Gondwana on the orogen's western side, while the subduction of the Rheic ocean continued and accommodated the convergence at its eastern realm. The western Rheic remnant subduction allowed the slight clockwise rotation of Gondwana suggested by paleomagnetism (Gallo et al., 2017; Torsvik et al., 2012). The rotation of Gondwana produced a buttress effect, which together with the protracted northwards convergence, led to a change in the stress field and buckled the previously formed orogen at the Rheic western realm between 320 Ma and 270

Ma. Orogen buckling and its associated strike slip deformation accommodated the shortening imposed in Pangea's interior. Whereas, subduction initiated (and or the mid-ocean ridge subducted) along the northern margin of the Paleotethys ocean (Gutiérrez-Alonso et al., 2008), which accommodated the convergence within the Paleotethys. The sustained northwards convergence of Gondwana likely contributed to the buckling of the Kazakhstan arc and closing of the western Central Asian Orogenic belt in the Permian (Li et al., 2018) (Fig. 3 and Supplementary Videos).

The widespread magmatic activity in the core of Pangea within the time frame 320 to 270 Ma is consistent with a hemispheric subduction initiation within the Paleotethys ocean (Gutiérrez-Alonso et al., 2008; van Hinsbergen et al., 2020). Subduction initiation and/or ridge subduction triggered major slab pull and roll back effects in the north and southern Paleotethyan realms (Fig. 3 and Supplementary Videos). Both processes, perhaps together, could be responsible for initiating the opening of the Neotethys Ocean during the early to mid-Permian (290-270 Ma) after Cimmeria rifted apart from Gondwana (Domeier & Torsvik, 2014; Gutiérrez-Alonso et al., 2008). From 270 Ma the northwards migration of Cimmeria and the enhanced subduction of the Paleotethys accommodated most northwards migration of Gondwana, establishing the new plate kinematic system. From 270 Ma, geological and paleomagnetic data suggest that Pangea became a rigid large scale plate until about 240 Ma, when extension began and nucleated the future central Atlantic Ocean, which opened ca. 200 Ma (Müller et al., 2019).

Subduction initiation/ridge subduction along the Paleotethys can explain the hiatus of lawsonite blueschists during the Permian (Tsujimori & Ernst, 2014). The Absence of lawsonite in high pressure rocks indicates hotter subduction zones, for example during subduction of the youngest parts of the ocean lithosphere. In addition, the model of this paper allows to speculate on the effect of these newly developed subduction zones on the core-mantle boundary. The subduction zones developed in the Paleotethyan realm occurred approximately over the large indent in the northern area of the low shear velocity province TUZO (Burke et al., 2008) evoking the possibility of a cause-effect relationship. Permian subducting slabs of the Paleotethys might have modified the shape of this low shear velocity province after falling over it. However, the size and volume of these slabs is moderate and therefore the link may be casual.

The recognition of major late Carboniferous - early Permian continental scale deformation and subduction initiation in the Paleotethys is consistent with paleomagnetic datasets (Fig. 2 and S1) and with late Carboniferous and Permian geologic database. The reconstruction presented here shows virtually no overlapping of continents due to incompatible paleolatitudes (Fig. 2B and C), and therefore there is no need for invoking >3,500 of an intra-Pangean dextral megashear(Bachtadse et al., 2018; Kent & Muttoni, 2020) during the Permian, which has never been documented. In addition, the reconstruction can explain why Pangea did not separated in Europe following the sutures of the former Iapetus/Rheic oceans as predicted by a traditional view of the Wilson cycle (Fig. 1). The reconstruction acknowledges that most intervening plates acted as large land-mass for over 100 Myr, which had a large influence in external geological processes such as changes in sea-level, biogeochemistry, and global climate. In contrast, in this model plates amalgamated into a Pangea super-plate only for a brief period of 30 to 50 Myr:. The participant plates remained independent, and actively interacting with each other and the underlying mantle, until ~270 Ma. The first evidences of extension within Pangea dated 240 Ma and the central Atlantic rifting was ongoing ca. 220 Ma (Müller et al., 2019). This model begs for a reassessment of Pangea as a template for other supercontinents or the supercontient cycle itself. Pangea acted as a super-plate for a too short period of time to have the influence in the mantle and core geodynamics that conceptual and numerical models predict for supercontinents and supercontinent cycles (Coltice et al., 2009; Heron, 2019; Yoshida & Santosh, 2011).

Acknowledgments, Samples, and Data

This work has been funded by a MEXT/JSPS KAKENHI Grant (JP16F16329) awarded to DPG. DPG would like to acknowledge M.J. Dekkers, C. Langereis, T. Tsujimori, John Geissman, R. van der Voo, and D.J.J. van Hinsbergen for endless discussions about the reconstruction. This paper is a contribution to UNESCO's IGCP 648: Supercontinent Cycles & Global Geodynamics.

Competing interests: The author declares no competing interest

Data and materials availability: This paper contains no new data. Paleomagnetic data used for this research are listed in supplementary Table S1 with all the corresponding references to each paleomagnetic pole.

References

Angiolini, L., Gaetani, M., Muttoni, G., Stephenson, M. H., & Zanchi, A. (2007). Tethyan oceanic currents and climate gradients 300 m.y. ago. Geology, 35(12), 1071–1074. https://doi.org/10.1130/G24031A.1

Bachtadse, V., Aubele, K., Muttoni, G., Ronchi, A., Kirscher, U., & Kent, D. V. (2018). New early Permian paleopoles from Sardinia confirm intra-Pangea mobility. Tectonophysics, 749, 21–34. https://doi.org/10.1016/J.TECTO.2018.10.012

Boscaini, A., Marzoli, A., Davies, J. F. H. L., Chiaradia, M., Bertrand, H., Zanetti, A., et al. (2020). Permian post-collisional basic magmatism from Corsica to the Southeastern Alps. Lithos, 376–377, 105733. https://doi.org/10.1016/j.lithos.2020.105733

Burke, K. (2011). Plate Tectonics, the Wilson Cycle, and Mantle Plumes: Geodynamics from the Top. Annual Review of Earth and Planetary Sciences (Vol. 39, p. 29). Annual Reviews. https://doi.org/10.1146/annurev-earth-040809-152521

Burke, K., Steinberger, B., Torsvik, T. H., & Smethurst, M. A. (2008). Plume Generation Zones at the margins of Large Low Shear Velocity Provinces on the core-mantle boundary. Earth and Planetary Science Letters, 265(1–2), 49–60. https://doi.org/10.1016/j.epsl.2007.09.042

Campbell, I. H., & Allen, C. M. (2008). Formation of supercontinents linked to increases in atmospheric oxygen. Nature Geoscience, 1(8), 554–558. https://doi.org/10.1038/ngeo259

Chen, S., Pe-Piper, G., Piper, D. J. W., & Guo, Z. (2014). Ophiolitic mélanges in crustal-scale fault zones: Implications for the Late Palaeozoic tectonic evolution in West Junggar, China. Tectonics, 33(12), 2419–2443. https://doi.org/10.1002/2013TC003488

Coltice, N., Phillips, B. R., Bertrand, H., Ricard, Y., & Rey, P. (2007). Global warming of the mantle at the origin of flood basalts over supercontinents. Geology, 35(5), 391–394. https://doi.org/10.1130/G23240A.1

Coltice, Nicolas, Bertrand, H., Rey, P., Jourdan, F., Phillips, B. R., & Ricard, Y. (2009). Global warming of the mantle beneath continents back to the Archaean. Gondwana Research, 15(3–4), 254–266. https://doi.org/10.1016/j.gr.2008.10.001

Correia, P., & Murphy, J. B. (2020). Iberian-Appalachian connection is the missing link between Gondwana and Laurasia that confirms a Wegenerian Pangaea configuration. Scientific Reports, 10(1), 1–7. https://doi.org/10.1038/s41598-020-59461-x

Domeier, M., & Torsvik, T. H. (2014). Plate tectonics in the late Paleozoic. Geoscience Frontiers, 5(3), 303–350. https://doi.org/10.1016/j.gsf.2014.01.002

Domeier, M., & Torsvik, T. H. (2019). Full-plate modelling in pre-Jurassic time. Geological Magazine, 156(2), 261–280. https://doi.org/10.1017/S0016756817001005

Domeier, M., Van Der Voo, R., & Torsvik, T. H. (2012). Paleomagnetism and Pangea: The road to reconciliation. Tectonophysics, 514–517, 14–43. https://doi.org/10.1016/j.tecto.2011.10.021

Edel, J. B., Schulmann, K., Lexa, O., & Lardeaux, J. M. (2018). Late Palaeozoic palaeomagnetic and tectonic constraints for amalgamation of Pangea supercontinent in the European Variscan belt. Earth-Science Reviews, 177(September 2017), 589–612. https://doi.org/10.1016/j.earscirev.2017.12.007

Evans, D. A. D. D. (2013). Reconstructing pre-Pangean supercontinents. Geological Society of America Bulletin, 125(11–12), 1735–1751. https://doi.org/10.1130/B30950.1

Gaggero, L., Gretter, N., Langone, A., & Ronchi, A. (2017). U–Pb geochronology and geochemistry of late Palaeozoic volcanism in Sardinia (southern Variscides). Geoscience Frontiers, 8(6), 1263–1284. https://doi.org/10.1016/j.gsf.2016.11.015

Gallo, L. C., Tomezzoli, R. N., & Cristallini, E. O. (2017). A pure dipole analysis of the Gondwana apparent polar wander path: Paleogeographic implications in the evolution of Pangea. Geochemistry, Geophysics, Geosystems, 18(4), 1499–1519. https://doi.org/10.1002/2016GC006692

Gardiner, N. J., Kirkland, C. L., & Van Kranendonk, M. J. (2016). The Juvenile Hafnium Isotope Signal as a Record of Supercontinent Cycles. Scientific Reports, 6, 38503–38503. https://doi.org/10.1038/srep38503

Gutiérrez-Alonso, G., Fernández-Suárez, J., Weil, A. B., Brendan Murphy, J., Damian Nance, R., Corf, F., & Johnston, S. T. (2008). Self-subduction of the Pangaean global plate. Nature Geoscience, 1(8), 549–553. https://doi.org/10.1038/ngeo250

Gutiérrez-Alonso, G., Fernández-Suárez, J., Jeffries, T. E. T. E. E., Johnston, S. T. S. T. S. T. T., Pastor-Galán, D., Murphy, J. B. B., et al. (2011). Diachronous post-orogenic magmatism within a developing orocline in Iberia, European Variscides. Tectonics, 30(5), 17 PP.-17 PP. https://doi.org/10.1029/2010TC002845

Heron, P. J., & Lowman, J. P. (2010). Thermal response of the mantle following the formation of a “super-plate.” Geophysical Research Letters, 37(22), n/a--n/a. https://doi.org/10.1029/2010GL045136

Heron, Philip J. (2019). Mantle plumes and mantle dynamics in the Wilson cycle. Geological Society, London, Special Publications, 470(1), 87–103. https://doi.org/10.1144/SP470-2018-97

van Hinsbergen, D. J. J., Torsvik, T. H., Schmid, S. M., Maţenco, L. C., Maffione, M., Vissers, R. L. M., et al. (2020). Orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic. Gondwana Research, 81, 79–229. https://doi.org/10.1016/j.gr.2019.07.009

Isozaki, Y., Aoki, K., Nakama, T., & Yanai, S. (2010). New insight into a subduction-related orogen: A reappraisal of the geotectonic framework and evolution of the Japanese Islands. Gondwana Research, 18(1), 82–105. https://doi.org/10.1016/j.gr.2010.02.015

Jian, P., Liu, D., & Sun, X. (2008). SHRIMP dating of the Permo-Carboniferous Jinshajiang ophiolite, southwestern China: Geochronological constraints for the evolution of Paleo-Tethys. Journal of Asian Earth Sciences, 32(5–6), 371–384. https://doi.org/10.1016/J.JSEAES.2007.11.006

Kent, D. V., & Muttoni, G. (2020). Pangea B and the Late Paleozoic Ice Age. Palaeogeography, Palaeoclimatology, Palaeoecology, 553, 109753. https://doi.org/10.1016/j.palaeo.2020.109753

Kneller, E. A., Johnson, C. A., Karner, G. D., Einhorn, J., & Queffelec, T. A. (2012). Inverse methods for modeling non-rigid plate kinematics: Application to mesozoic plate reconstructions of the Central Atlantic. Computers & Geosciences, 49, 217–230. https://doi.org/10.1016/j.cageo.2012.06.019

Lamotte, D. F. de, Fourdan, B., Leleu, S., Leparmentier, F., & Clarens, P. de. (2015). Style of rifting and the stages of Pangea breakup. Tectonics, 34(5), 1009–1029. https://doi.org/10.1002/2014TC003760

Li, P., Sun, M., Rosenbaum, G., Yuan, C., Safonova, I., Cai, K., et al. (2018). Geometry, kinematics and tectonic models of the Kazakhstan Orocline, Central Asian Orogenic Belt. Journal of Asian Earth Sciences, 153(July 2017), 42–56. https://doi.org/10.1016/j.jseaes.2017.07.029

Matte, P. (2001). The Variscan collage and orogeny (480-290 Ma) and the tectonic definition of the Armorica microplate: a review. Terra Nova, 13(2), 122–128. https://doi.org/10.1046/j.1365-3121.2001.00327.x

McCann, T., Pascal, C., Timmerman, M. J., Krywiec, P., LÃ3pez-GÃ3mez, J., Wetzel, A., et al. (2006). Post-Variscan (End Carboniferous-Early Permian) basin evolution in Western and Central Europe. In D. Gee & R. A. Stephenson (Eds.) (pp. 355–388). London: Geological Society.

Müller, R. D., Zahirovic, S., Williams, S. E., Cannon, J., Seton, M., Bower, D. J., et al. (2019). A Global Plate Model Including Lithospheric Deformation Along Major Rifts and Orogens Since the Triassic. Tectonics, 38(6), 1884–1907. https://doi.org/10.1029/2018TC005462

Nance, R. D., Gutiérrez-Alonso, G., Keppie, J. D., Linnemann, U., Murphy, J. B., Quesada, C., et al. (2010). Evolution of the Rheic Ocean. Gondwana Research, 17(2–3), 194–222. https://doi.org/10.1016/j.gr.2009.08.001

Nance, R. D., Murphy, J. B., & Santosh, M. (2014). The supercontinent cycle: A retrospective essay. Gondwana Research, 25(1), 4–29. https://doi.org/10.1016/j.gr.2012.12.026

Pastor-Galan, D., Groenewegen, T., Brouwer, D., Krijgsman, W., Dekkers, M. J., Pastor-galán, D., et al. (2015). One or two oroclines in the Variscan orogen of Iberia? Implications for Pangea amalgamation. Geology, 43(6), 527–530. https://doi.org/10.1130/G36701.1

Pastor-Galán, D., Pueyo, E. L., Diederen, M., García-Lasanta, C., & Langereis, C. G. (2018). Late Paleozoic Iberian Orocline(s) and the Missing Shortening in the Core of Pangea.

Paleomagnetism From the Iberian Range. Tectonics, 37(10), 3877–3892. https://doi.org/10.1029/2018TC004978

Pastor-Galán, D., Nance, R. D., Murphy, J. B., & Spencer, C. J. (2019). Supercontinents: myths, mysteries, and milestones. Geological Society, London, Special Publications, 470, 39–64. https://doi.org/10.1144/SP470.16

Pastor-Galán, D., Dias da Silva, Í. F., Groenewegen, T., & Krijgsman, W. (2019). Tangled up in folds: tectonic significance of superimposed folding at the core of the Central Iberian curve (West Iberia). International Geology Review, 61(2), 240–255. https://doi.org/10.1080/00206814.2017.1422443

Pastor-Galán, D., Gutiérrez-Alonso, G., & Weil, A. B. (2020). The enigmatic curvature of Central Iberia and its puzzling kinematics. Solid Earth, 11(4), 1247–1273. https://doi.org/10.5194/se-11-1247-2020

Pereira, M. F., Castro, A., Chichorro, M., Fernández, C., Díaz-Alvarado, J., Martí, J., & Rodríguez, C. (2014). Chronological link between deep-seated processes in magma chambers and eruptions: Permo-Carboniferous magmatism in the core of Pangaea (Southern Pyrenees). Gondwana Research, 25(1), 290–308. https://doi.org/10.1016/J.GR.2013.03.009

Shafaii Moghadam, H., & Stern, R. J. (2014). Ophiolites of Iran: Keys to understanding the tectonic evolution of SW Asia: (I) Paleozoic ophiolites. Journal of Asian Earth Sciences, 91, 19–38. https://doi.org/10.1016/j.jseaes.2014.04.008

Spencer, C. J., Hawkesworth, C., Cawood, P. a., Dhuime, B., Spencer, C. J., Hawkesworth, C., et al. (2013). Not all supercontinents are created equal: Gondwana-Rodinia case study. Geology, 41(7), 795–798. https://doi.org/10.1130/G34520.1

Stampfli, G. M., Hochard, C., Vérard, C., Wilhem, C., & VonRaumer, J. (2013). The Formation of Pangea. Tectonophysics, 593, 1–19. https://doi.org/10.1016/j.tecto.2013.02.037

Steinberger, B., & Torsvik, T. H. (2008). Absolute plate motions and true polar wander in the absence of hotspot tracks. Nature, 452(7187), 620–623. https://doi.org/10.1038/nature06824

Torsvik, T. H., & Cocks, L. R. M. (2017). Earth history and palaeogeography (p. 317). Retrieved from https://books.google.co.jp/books?hl=en&lr=&id=j6hsDQAAQBAJ&oi=fnd&pg=PP10&ots=cFoWCcWDm3&sig=ihfe3sttl-2J12-BmUyN_oDtDNo&redir_esc=y#v=onepage&q&f=false

Torsvik, T. H., Burke, K., Steinberger, B., Webb, S. J., & Ashwal, L. D. (2010). Diamonds sampled by plumes from the core–mantle boundary. Nature, 466(7304), 352–355. https://doi.org/10.1038/nature09216

Torsvik, T. H., Voo, R. V. D., Preeden, U., Mac, C., Steinberger, B., Doubrovine, P. V., et al. (2012). Phanerozoic polar wander, palaeogeography and dynamics. Earth-Science Reviews, 114(3–4), 325–368. https://doi.org/10.1016/j.earscirev.2012.06.007

Tsujimori, T., & Ernst, W. G. (2014). Lawsonite blueschists and lawsonite eclogites as proxies for palaeo-subduction zone processes: a review. Journal of Metamorphic Geology, 32(5), 437–454. https://doi.org/10.1111/jmg.12057

Turrillot, P., Augier, R., Monié, P., & Faure, M. (2011). Late orogenic exhumation of the Variscan high-grade units (South Armorican Domain, western France), combined structural and 40Ar/39Ar constraints. Tectonics, 30, 27 PP.-27 PP. https://doi.org/10.1029/2010TC002788

Weil, A. B. B., Gutiérrez-Alonso, G., Johnston, S. T., & Pastor-Galán, D. (2013). Kinematic constraints on buckling a lithospheric-scale orocline along the northern margin of Gondwana: A geologic synthesis. Tectonophysics, 582, 25–49. https://doi.org/10.1016/j.tecto.2012.10.006

Wilson, B. M. (2004). Permo-carboniferous magmatism and rifting in Europe (p. 514). Geological Society.

Wu, L., Murphy, J. B., Quesada, C., Li, Z.-X., Waldron, J. W. F., Williams, S., et al. (2020). The amalgamation of Pangea: Paleomagnetic and geological observations revisited. GSA Bulletin. https://doi.org/10.1130/B35633.1

Yeh, M.-W., & Shellnutt, J. G. (2016). The initial break-up of Pangæa elicited by Late Palæozoic deglaciation. Scientific Reports, 6(1), 1–9. https://doi.org/10.1038/srep31442

Yoshida, M., & Hamano, Y. (2015). Pangea breakup and northward drift of numerical model of mantle convection. Scientific Reports, 5, 8407–8407. https://doi.org/10.1038/srep08407

Yoshida, M., & Santosh, M. (2011). Supercontinents, mantle dynamics and plate tectonics: A perspective based on conceptual vs. numerical models. Earth-Science Reviews, 105(1), 1–24.

Zeh, A., Hansch, R., Bratz, H., & Bombach, K. (2000). Provenance and alteration of granite gravels in Rotliegend beds from the northwestern Thuringian Forest: Results of petrography, geochemistry and zircon investigations. Neues Jahrbuch Fur Geologie Und Palaontologie-Abhandlungen, 218(1–2), 173–199.

Zhang, X.-Z., Dong, Y.-S., Wang, Q., Dan, W., Zhang, C., Deng, M.-R., et al. (2016). Carboniferous and Permian evolutionary records for the Paleo-Tethys Ocean constrained by newly discovered Xiangtaohu ophiolites from central Qiangtang, central Tibet. Tectonics, 35(7), 1670–1686. https://doi.org/10.1002/2016TC004170

Zi, J.-W., Cawood, P. A., Fan, W.-M., Wang, Y.-J., & Tohver, E. (2012). Contrasting rift and subduction-related plagiogranites in the Jinshajiang ophiolitic mélange, southwest China, and implications for the Paleo-Tethys. Tectonics, 31(2). https://doi.org/10.1029/2011TC002937

Ziegler, P. A. (1990). COLLISION RELATED INTRA-PLATE COMPRESSION DEFORMATIONS IN WESTERN AND CENTRAL-EUROPE. Journal of Geodynamics, 11(4), 357–388.

Fig. 1. The Two faces of Pangea (a) Classic views of Pangea A and B during the late Carboniferous, with a line marking the equator and the accepted Early Triassic Pangea A. b) Distribution of the landmasses, present-day plate boundaries and oceanic sutures in the core of Pangea. Note that counterintuitively, Pangea broke too far from some pre-existing oceanic sutures and weak lithospheric zones, even cross cutting cratonic areas.

Fig. 2. a) Plot showing the vertical axis rotations in the core of Pangea. expected declination of the studied paleomagnetic data-set from Europe and East North America compared with the global apparent polar wander path rotated to Baltica (Torsvik et al., 2012). A clockwise rotation of NW Europe and NE America and a counterclockwise rotation of the Iberian peninsula and

some areas of the Mediterranean are shown by the dataset. For errors see Figure S1. b) Global Apparent Polar Wander Path (GAPWaP) rotated to the Gondwana coordinates and c) to and Laurussia A) shows poles from volcanic rocks and inclination corrected sedimentary rocks that were not included in Gallo et al. APWP. The only pole that does not fit is that from Adria (e.g. Kent and Muttoni, 2020) Reference location is county Cork, Ireland: 52˚ N, -9˚ E.

Fig. 3. Formation of Pangea. Plate reconstruction of the core of Pangea. The continuing northwards convergence of Gondwana leading to a change in the stress field in the Variscan orogen, which produced shortening, vertical axis rotations and localized extension. Synchronous subduction initiation/ridge failure/ridge subduction occurred in the Paleotethys around 300 Ma. After the opening of the Neotethys, migration of Cimmeria northwards, and amalgamation of Siberia craton to Laurussia, Pangea became a rigid super-plate by about 270 Ma. The lithospheric scale structures formed during the period 320-270 Ma may explain why Pangea broke up where it did in the North Atlantic did not follow the previous sutures.

Figure 1.

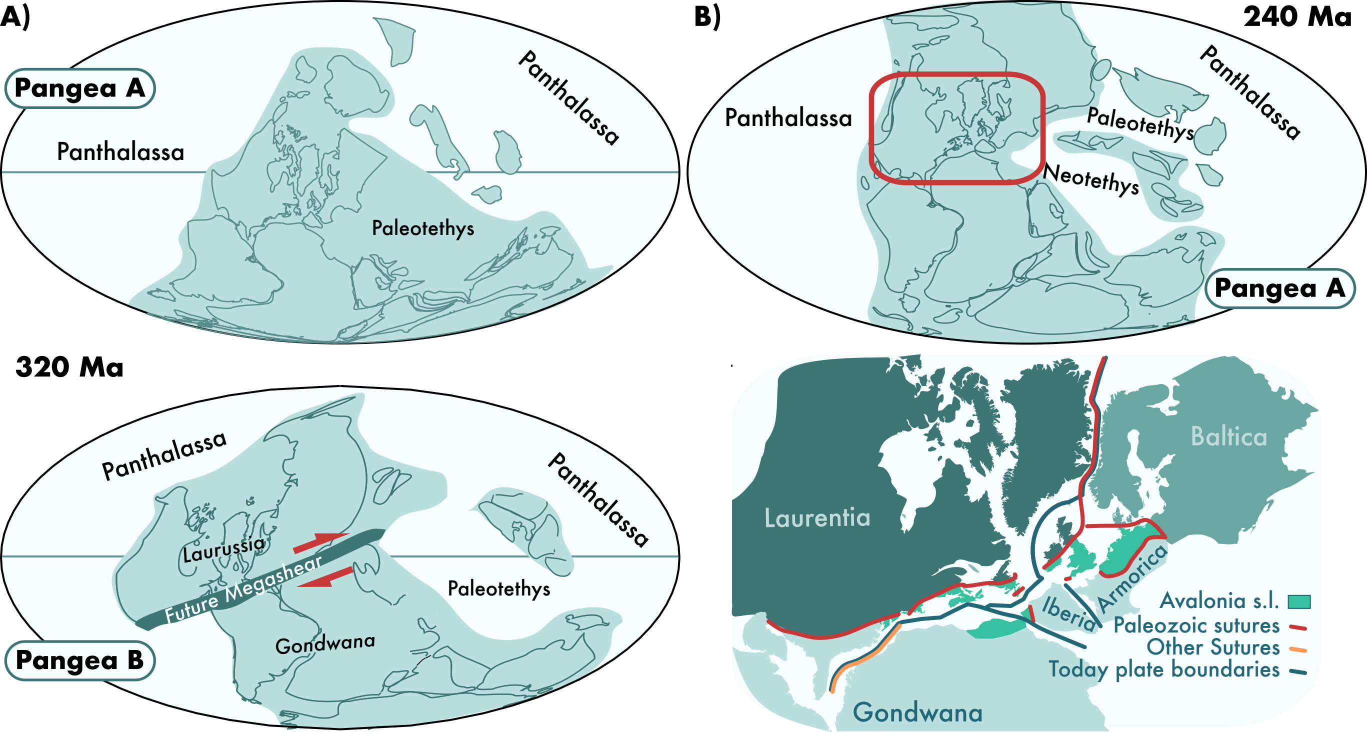
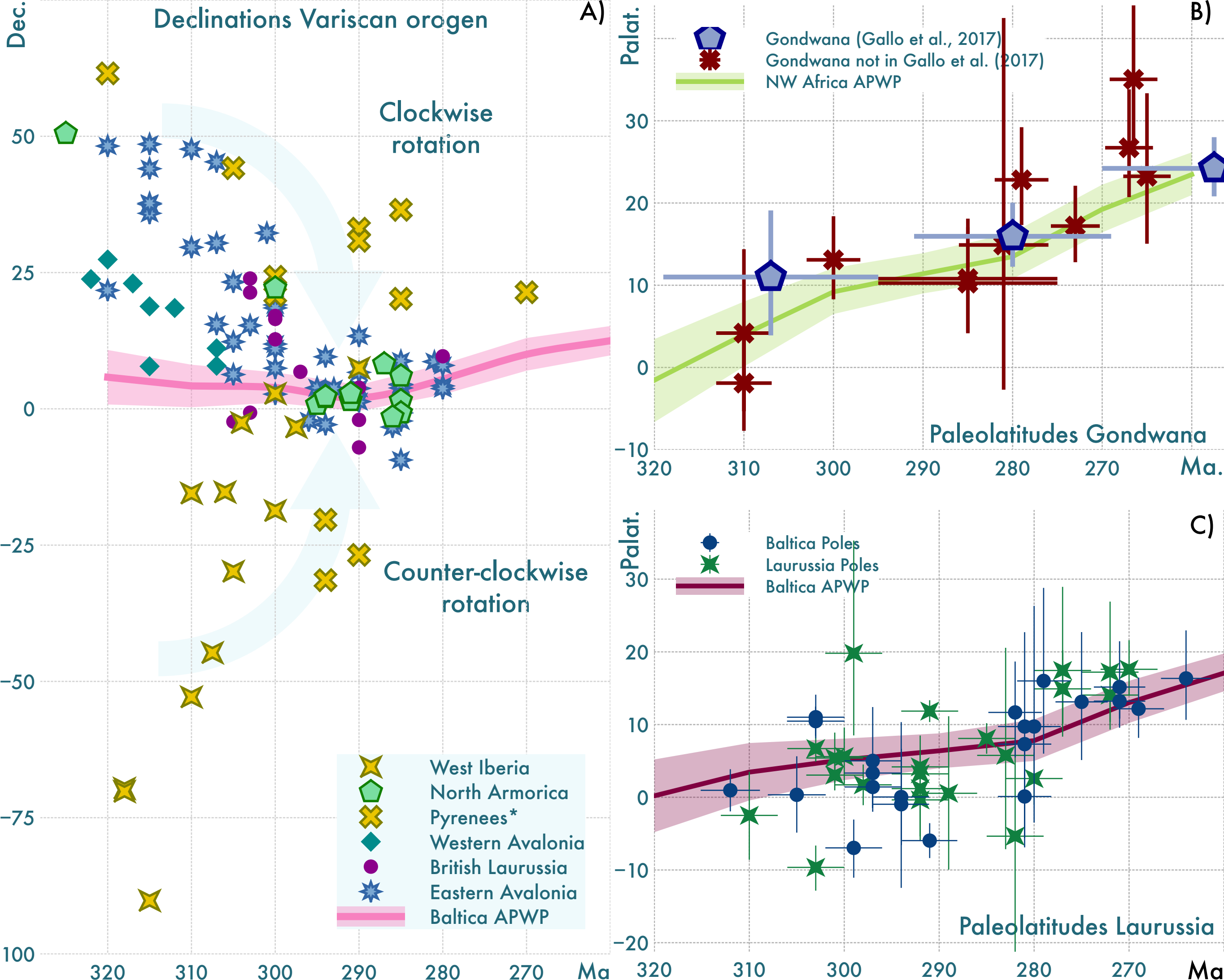
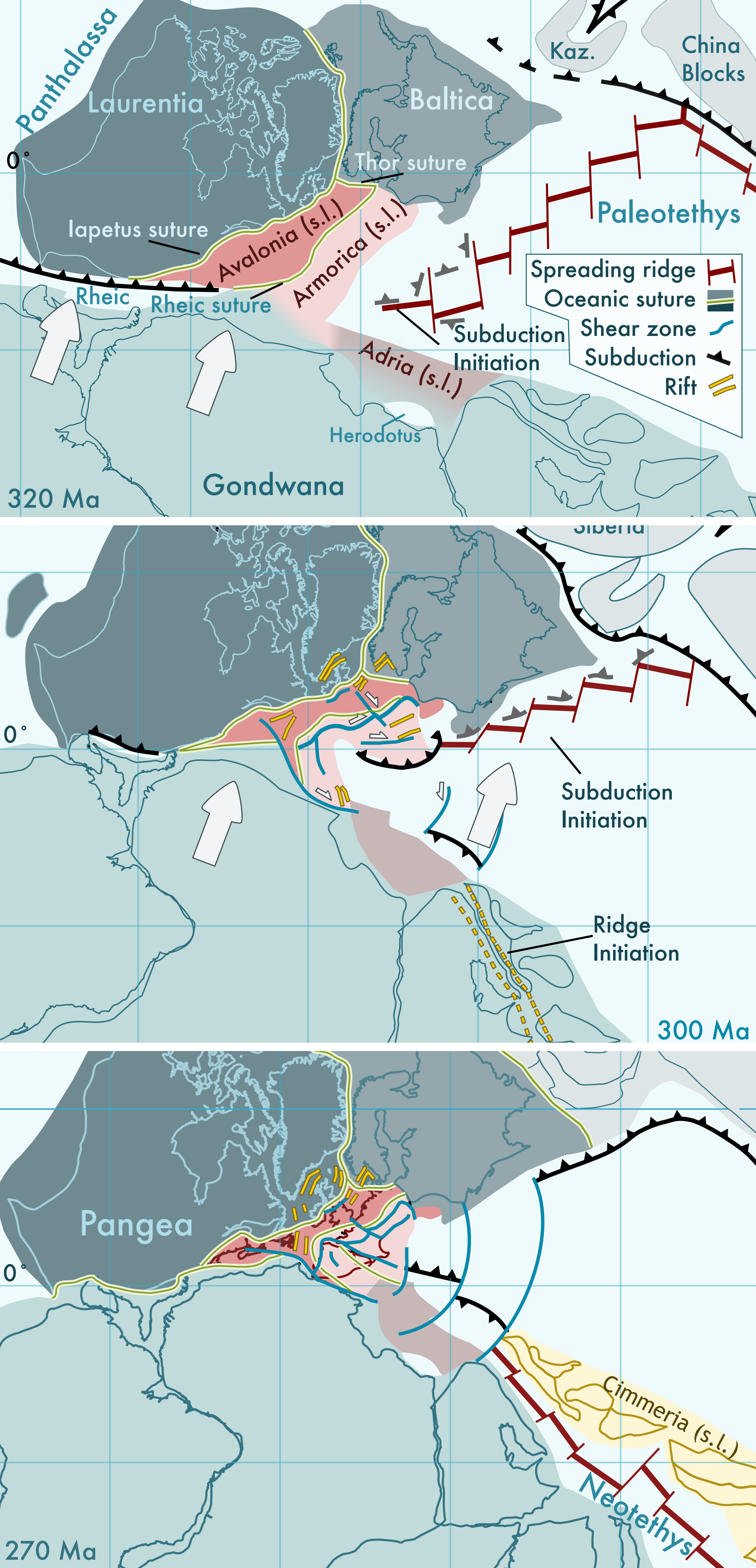

A)
Pangea A
Panthalassa
Panthalassa
Paleotethys
320 Ma
Panthalassa
Panthalassa
Laurussia
Future Megashear
Paleotethys
Gondwana
Pangea B
B)
240 Ma
Panthalassa
Panthalassa
Paleotethys
Neotethys
Pangea A
Laurentia
Baltica
Iberia
Armorica
Gondwana
Avalonia s.l.
Paleozoic sutures
Other Sutures
Today plate boundaries

Figure 2.



A)
Declinations Variscan orogen
Dec.
Clockwise rotation
Counter-clockwise rotation
West Iberia
North Armorica
Pyrenees*
Western Avalonia
British Laurussia
Eastern Avalonia
Baltica APWP
Ma
B)
Palat.
Gondwana (Gallo et al., 2017)
Gondwana not in Gallo et al. (2017)
NW Africa APWP
Paleolatitudes Gondwana
Ma.
C)
Palat.
Baltica Poles
Laurussia Poles
Baltica APWP
Paleolatitudes Laurussia
Ma

Figure 3.


Panthalassa
Laurentia
Baltica
Kaz.
China Blocks
0°
Thor suture
Paleotethys
Iapetus suture
Avalonia (s.l.)
Armorica (s.l.)
Spreading ridge
Oceanic suture
Shear zone
Subduction
Rift
Subduction Initiation
Rheic
Rheic suture
Adria (s.l.)
Herodotus
Gondwana
320 Ma
0°
Subduction Initiation
Ridge Initiation
300 Ma
Pangea
0°
Cimmeria (s.l.)
Neotethys
270 Ma